

Guilt by Association: Finding Cosmic Ray Sources Using Hierarchical Bayesian Clustering

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1 Introduction

Since the Pierre Auger Observatory (PAO) initiated observations in 2004 it has detected 14 ultra high energy cosmic rays (UHECRs) with energy ≥ 55 Eev in period 1–January 1, 2004 - May 26, 2006, 13 UHECRs in period 2– May 27, 2006 - August 31, 2007, and 42 UHECRs in period 3– September 1, 2007 - December 31, 2009. The energy threshold of 55 Eev was chosen by using period 1 data [1]. These CR particles interact with the cosmic microwave background, and according to GZK limit, CRs with energy $\gtrsim 60$ Eev should come from sources within 200 Mpc [1]. We consider the 17 active galactic nuclei (AGNs) in the volume-complete (to 15 Mpc) catalog of [3] as candidate sources. We use a Bayesian hierarchical model to compare 3 models, M_0 : only isotropic background source, M_1 : isotropic background + 17 AGNs, M_2 : isotropic background + 2 AGNs (Centaurus A and NGC 4945—the two closest AGNs) for the UHECRs from the three periods.

2 Models and Algorithms

We describe the CR arrival as a Poisson process with rate set by source fluxes and exposure factors, the measurement error as a Fisher distribution with the angular uncertainty of 0.9° and the magnetic deflection as a Fisher distribution with concentration parameter κ . Our hierarchical model has parameters F_0 (flux from isotropic background), F_A (total flux from the AGNs), λ (source label of each UHECR), and κ . We assume AGNs have fixed CR luminosity implying an AGN at distance d

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generates CR flux $\propto 1/d^2$. We analyze a physically plausible range of deflections $\kappa \in [1, 1000]$. F_0 and F_A have an exponential prior with scale $s \approx 0.063 \text{ km}^{-2} \text{ yr}^{-1}$, based on previous data from CR observatories AGASA and HiRes. Gibbs sampling is performed on the parameters F_A, F_0 and λ to obtain the posterior distributions. We use Chib's method in [2] to estimate the marginal likelihood under each model.

3 Results

The Bayes factors as a function of κ are shown in Fig. 1. Adopting the log-flat prior for κ , we obtain the overall Bayes factor against the null of 26.10, 5.41 and 0.15 for M_1 and 12.37, 8.27 and 0.11 for M_2 , for periods 1, 2 and 3, respectively. The strength of the evidence for AGN association differs markedly from period to period. For M_1 and M_2 we find $\lesssim 10\%$ of PAO CRs may come from AGN and a significant fraction must originate elsewhere.

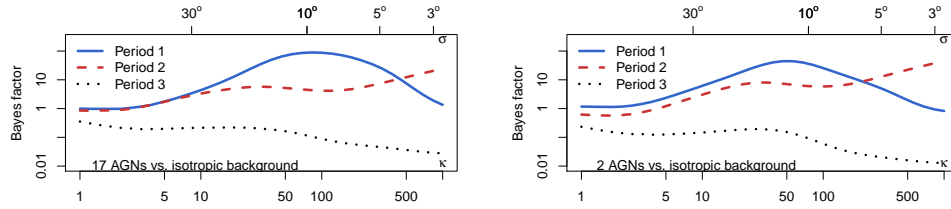


Fig. 1 Bayes factors comparing the association model with 17 AGNs (left) or 2 AGNs (right) to the null isotropic background model. σ is the standard deviation in 2-d Gaussian approximation for the Fisher distribution

References

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